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AS A RESULT OF GAS CONDENSATION

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FORMATION OF DUST PARTICLES IN A COMET ATMOSPHERE AS A RESULT OF GAS CONDENSATION

A. Z. Dolginov

ABSTRACT. Consideration of gas condensation near a comet nucleus as a source of the formation of the entire dust component of the comet coma. It is maintained that available observational data do not discount the possibility of this origin of comet dust. A theory is proposed to explain the mechanism of the process. It holds that secondary gas molecules (C_2 , CN, etc) are formed from the primary molecules of a comet nucleus (CH_4 , NH_3 , etc) and that the concentration and the number of collisions of these secondary molecules are sufficient for the formation of stable nuclei of a solid phase.

1. Formulation of the Problem

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The occurrence of gas and dust in the atmosphere of a comet is usually explained by the fact that its nucleus represents a conglomeration of different ices which vigorously evaporate at comparatively low temperatures (for example, CH_4 , NH_3 , etc) and high-melting inclusions in the form of dust particles. During the ice evaporation, the dust particles are carried away by gas currents.

We shall show that existing data on the nature of comets do not contradict another possible explanation for the coma dust component -- namely, the possible formation of dust particles when gases condense near the nucleus. Naturally, gases which are evaporated from the nucleus surface cannot be condensed again. However, the life-time of these gases is small. The majority of observed spectral lines of the coma belong to secondary modules (C_2 , CN, etc), which cannot be directly evaporated from the nucleus surface under the influence of solar radiation. The formation of secondary particles is caused by dissociation of primary particles under the influence of electromagnetic and corpuscular radiation of the sun, and chemical reactions. Secondary gases may be formed as supersaturated gases, and may be condensed under suitable conditions. Carbon is one of these gases; it may possibly be responsible for the formation of dust particles.

We shall show the following: a) if substances containing carbon -- for example, hydrocarbons -- are evaporated from the surface of a comet nucleus, they dissociate or enter into chemical reactions, with the formation of a carbon supersaturated vapor; b) the degree of supersaturation and the number of collisions between the molecules are sufficient for forming stable nuclei of a solid phase; c) particle concentration close to the nucleus is sufficient to increase the size of the dust particles up to $\sim 10^{-5}$ - 10^{-4} cm, and even up to 10^{-3} - 10^{-2} cm when there is a small concentration of them; d) not only carbon, but also

* Note: Numbers in the margin indicate pagination in the original foreign text.

other substances with a high heat of evaporation may be included in the composition of dust particles; e) since chemical reactions and dissociation processes may be sharply accelerated under the influence of hard electromagnetic or corpuscular solar radiation, the formation of dust, and the increase in the coma brightness which is connected with it, must be correlated with solar activity.

2. Gas Concentration Close to the Nucleus

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Before investigating the formation of dust, let us determine the gas density. Direct study of comet spectra does not yield complete information on the density and chemical composition of the coma, since not all of its molecules have lines in the visible spectral region. Therefore, we must resort to an indirect method. We may determine the dust mass from the intensity of the continuous spectrum. All of the hypotheses regarding the nature of comets stipulate that the gas mass in the atmosphere of the comet exceeds the dust mass. A study of the dust density in the tails of the comets Arend-Roland and Markos led Liller (Ref. 1) to the conclusion that the nucleus loses $8 \cdot 10^7 - 10^9$ g/sec of substance on the average at a distance of ~ 1 AU from the sun. Assuming that the mean molecular weight of the evaporated molecules ~ 20 , we obtain an evaporation intensity of $Q \sim 10^{30} - 10^{31}$ particle/sec·ster. Biermann and Trefftz (Ref. 2) obtained this estimate for Q , based on the experimental data for the intensity of the forbidden green line of oxygen in the spectra of comet heads. Hübner (Ref. 3) investigated the evaporation of an ice nucleus, with allowance for the optical thickness of the coma, the albedo of the nucleus, its thermal radiation, etc, under different assumptions regarding the ice composition (C_2H_2 , CH_4 , CO_2 , etc). He compared the computational results with observations of the brightness of twenty different comets. It was found that for almost all of them the quantity $Q/R^2 = 10^8$ molecule/cm²·sec·ster, where R is the radius of the comet nucleus. For $R = 10^8$ cm, this corresponds to $Q = 10^{30}$ molecule/sec·ster. Thus, different estimations have led to the same value of Q . Since the number of collisions is quite large close to the nucleus, the particle distribution is close to a Maxwell distribution, and the kinetic equation determining the particle concentration may be written in the following form

$$\mathbf{v} \cdot \text{grad } N(r) = Q_1 \delta(r - R) \delta(n - n_v) - \frac{N(r)}{\tau}, \quad Q_1 = \frac{Q}{r^2}, \quad (1)$$

i.e., without a collision term. The particles are evaporated from the nucleus surface $r = R$. It is assumed that their velocity $\mathbf{v} = v\mathbf{n}_v$ is directed along $\mathbf{r} = r\mathbf{n}$. Therefore, the source is chosen in the form $Q_1 \delta(r - R) \delta(n - n_v)$ where $\delta(r - R)$ and $\delta(n - n_v)$ are δ -functions. τ is the particle lifetime; r -- distance to the nucleus center.

If the nucleus surface is the source of the particles, then the solution of equation (1) may be represented in the following form with good accuracy

$$N(r) = \frac{Q}{vr^2} \exp\left(-\frac{r - R}{v\tau}\right). \quad (2)$$

The evaporation of volatile ice at a distance of 1 AU from the sun occurs vigorously at a comparatively low temperature $< 200^\circ\text{K}$, i.e., the velocity of the primary molecules $< 5 \cdot 10^4$ cm/sec. Assuming that $r \ll v\tau$, $R = 10$ km and

substituting the assumed estimates for v and for Q into (2), we obtain $N \sim 10^{12} \text{ cm}^{-3}$ up to the distances 50 km and $N \sim 10^{11} \text{ cm}^{-3}$ to 150 km.

3. Formation of Secondary Molecules

The composition of gases, whose spectra have been observed in the atmospheres of comets, C_2 , CN , C_3 , OH , CH , NH_2 , CO^+ , CH^+ , N_2^+ , OH^+ , CO_2^+ , points to their secondary origin. This is apparent for ions and such high-melting substances as carbon, and is very probable for the free radicals CN , OH , etc. It is usually assumed that all of these gases are formed during the decomposition of primary molecules CH_4 , C_2H_2 , C_2N_2 , H_2O , CO_2 , NH_3 , etc. under the influence of photon and corpuscular radiation of the sun. The assumption that these molecules are parent molecules is based on their great abundance and simple chemical structure. For those molecule concentrations which occur close to the nucleus ($\sim 10^{13} - 10^{12} \text{ cm}^{-3}$), the mean free path is $10^2 - 10^3 \text{ cm}$ in all, i.e., the number of collisions is sufficient for chemical reactions to take place. Local heating which is necessary for an exothermal reaction to begin may be caused by many factors; the particles of corpuscular streams, electric discharge, the collision of nuclear fragments, etc. The reactions lead to heating of the gas, and also to intensification of the evaporation, if they encompass the nucleus surface. Observations of dust halos, which expand at a rate of $\geq 10^5 \text{ cm/sec}$, also provide direct proof of the high temperature close to the nucleus. Since the velocity of gas molecules must be greater than the velocity of the dust particles, the gas temperature must exceed 1000°K . However, the temperature of the nucleus surface cannot be greater than that at which vigorous evaporation is initiated ($\sim 100 - 200^\circ\text{K}$, i.e. $v \sim 5 \cdot 10^4 \text{ cm/sec}$). The high degree of ionization in the vicinity of the nucleus, which is observed for many comets, also points to the high effective temperature in this region. /436

Keeping in mind the investigation of gas condensation in a dust particle, let us first of all turn to reactions which lead to the formation of vapors which are saturated at the reaction temperature -- for example, carbon vapors. We shall assume that one of the primary particles is C_2H_2 . The acetylene decomposition reaction $\text{C}_2\text{H}_2 \rightarrow 2\text{C} + \text{H}_2 + 54 \text{ kcal}$ is greatly exothermic. Liquid and solid acetylene explode in the case of detonation or when an electric spark is passed. It is possible that acetylene ice occurs in the nucleus composition. It is also possible that acetylene is formed when the nucleus surface layer is heated, as a result of a certain reaction--for example, $\text{CaC}_2 + 2\text{H}_2\text{O} \rightarrow \text{C}_2\text{H}_2 + \text{Ca(OH)}_2 + 32 \text{ kcal}$. The decomposition of ethylene $\text{C}_2\text{H}_4 \rightarrow 2\text{C} + 2\text{H}_2 + 10 \text{ kcal}$ takes place similarly to acetylene decomposition. For $T \geq 1000^\circ\text{K}$, many hydrocarbons undergo thermal decomposition (pyrolysis) -- for example, $\text{CH}_4 \rightarrow \text{C} + 2\text{H}_2$. We may point to an entire series of reactions leading to the formation of carbon under conditions which are similar to conditions close to the nucleus. Unfortunately, we do not have information on primary substances, and all information on specific reactions is only illustrative in nature. Although the fact that the visual brightness of many comets is determined by the Swan bands, which belong to the C_2 molecule, clearly points to the most likely formation of carbon, we cannot unequivocally

indicate the mechanism by which it is formed. Therefore, the basic hypothesis which is necessary for the further discussion would be the assumption that carbon, or any other gas liberated in large amounts in the form of supersaturated vapor, is formed in the direct vicinity of the nucleus, where the density is sufficient to form dust particles. This hypothesis does not contradict any existing data, it is corroborated by several indirect considerations (appropriate conditions close to the nucleus for the requisite chemical reactions to take place, the probable composition of primary molecules, etc), and leads to conclusions which explain certain facts which cannot be understood from the customary point of view.

4. Formation of the Condensate Nuclei

Carbon heat of sublimation q equals $(7.5 - 10) \cdot 10^4$ erg/atom, and slightly depends on temperature. With a concentration of $N \sim 1.4 \cdot 10^{11}$ cm⁻³, the saturation temperature of carbon vapor is about 2500°K, i.e., close to the nucleus the vapor is greatly oversaturated. The formation of stable condensate nuclei is necessary for condensation to begin. Condensation occurs very readily in ions and dust particles. It is known (Ref. 4) that any ion is a stable nucleus, if the vapor temperature is such that the degree of oversaturation $\theta \geq \theta_h$, where

$$\theta = \frac{T - T_s}{T_s}, \quad \theta_h = \frac{3\omega\sigma^{\frac{1}{3}}}{2 \cdot 4^{1/3} k q} \left(\frac{16\pi}{e^3} \right)^{\frac{1}{3}}, \quad (3)$$

where T is the vapor temperature; T_s -- saturation temperature at a given pressure; ω -- volume of the condensed phase belonging to one atom; k -- the Boltzmann constant; e -- ion charge; σ -- surface tension. Although σ is unknown for carbon, it may be assumed that it does not exceed the maximum values which are known for other substances. Assuming that $\sigma < 5 \cdot 10^3$ erg/cm², $q \sim 8 \cdot 10^4$ erg/atom, $T \sim 2500^\circ\text{K}$, $T < 1000^\circ\text{K}$, and $\omega \approx 10^{-23}$ cm³, we obtain $\theta > \theta_h$, i.e., close to the nucleus, any ion is a stable nucleus of the dust particle.

When a substance evaporates from the nucleus surface, especially in the case of vigorous chemical reactions, microscopic droplets of the condensed phase may be carried away by the gas. Although these droplets are evaporated in a short period of time, nuclei of carbon or other high-melting dust particles are readily formed on their surface. A comparatively small number of nuclei is sufficient to form the observed amount of dust, since the number of molecules is greater than the number of dust particles by a factor of $10^8 - 10^{11}$. /437

5. Growth of Dust Particles

Let us determine the size of the dust particles formed, assuming that a condensed gas arises as a result of decomposition or chemical conversion of any primary molecules. If the formation of the secondary particles (in which we are interested) represents the basic channel for the disappearance of primary particles, employing (3) we obtain the following expression for the concentration of secondary particles

$$n(r) = \frac{Q}{vr^2} \left[1 - \exp \frac{R-r}{v\tau} \right]. \quad (4)$$

The growth of the dust particles is described by the following equation

$$\frac{dG}{dt} = \beta n v S \left[1 - \exp \left(-\frac{q\Theta}{kT} \right) \right], \quad (5)$$

$$G = \frac{4\pi}{3\omega} \rho^3, \quad S = 4\pi\rho^2, \quad (6)$$

where G is the number of atoms in the dust particle, and ρ is its radius.

We shall assume that the coefficient for molecules sticking to a dust particle β is close to unity. It may be readily shown that the quantity $\exp(-q\Theta/kT)$, which determines the dust particle evaporation rate, is very small for the assumed values of Θ , q and T , and may be omitted.

Taking the fact into account that $dr = vdt$, and substituting (4) and (6) in (5), we obtain

$$\frac{d\rho}{dr} = \beta \frac{Q}{vr^2} \left[1 - \exp \frac{R-r}{v\tau} \right], \quad (7)$$

$$\rho = \beta \frac{Q\omega}{vR} \left[-\frac{R}{v\tau} \text{Ei} \left(+\frac{R}{v\tau} \right) \right] \exp \left(\frac{R}{v\tau} \right), \quad (8)$$

where $\text{Ei}(x)$ is the integral exponential function. Employing the asymptotic expression for $\text{Ei}(x)$, we obtain

$$\rho = \beta \frac{Q\omega}{vR} \left[\frac{R}{v\tau} \ln \frac{v\tau}{R} - 0.577 \frac{R}{v\tau} + \left(\frac{R}{v\tau} \right)^2 - \right. \quad (9)$$

$$\left. - \frac{1}{4} \left(\frac{R}{v\tau} \right)^3 \right] \exp \left(\frac{R}{v\tau} \right) \quad \text{for } R \ll v\tau, \quad (10)$$

$$\rho = \beta \frac{Q\omega}{vR} \left[1 - \frac{v\tau}{R} + 6 \left(\frac{v\tau}{R} \right)^2 - \dots \right] \quad \text{for } R \gg v\tau.$$

The assumptions regarding the lifetime of primary molecules and the dust particle density play the basic role in further determinations. Assuming that $\omega \approx 1.2 \cdot 10^{-23} \text{ cm}^{-3}$ (density of graphite), $\beta \approx 0.5$, $Q \approx 10^{30}$ particle/sec, $v \approx 10^5$ cm/sec, and $\tau \sim 10$ -100 sec, we obtain $\rho \sim 10^{-4}$ - 10^{-5} cm, which corresponds to the observed size of dust particles. If the dust particle density is smaller, a greater lifetime for the primary particles is permissible.

We should note that the growth of dust particles can occur not only due to carbon atoms, but also due to atoms or molecules of other substances which are adsorbed or condensed in the dust particle. Several substances which are slightly condensed in pure form in the vicinity of the comet nucleus can be deposited in very small dust particles of carbon, thus providing for their rapid growth. If the concentration of these particles close to the nucleus is large, /438 they can determine the dust particle composition.

It is possible that particles of meteor streams differ from other dust particles in the atmosphere of the comet producing this stream only in terms of

their large size $\sim 10^{-2} - 10^{-3}$ cm. Observations have pointed to the anomalously small density of meteor particles. Their spectra contain the lines of different elements. As has already been indicated, the composite composition of dust particles may be readily explained by the assumption of different substances being deposited on the stable carbon nuclei. If the dust particle density is small, their radius can reach the observed amount. For $\omega \sim 10^{-21}$ cm⁻³ and $\tau \sim 10-100$ sec, we obtain $\rho \sim 10^{-2} - 10^{-3}$ cm from (9). When analyzing data on the reflection coefficient and the polarization of light scattered by the coma, we must recall the possible nonuniform composition of the dust particles.

6. Correlation With Solar Activity

The amount of dust particles in the atmosphere of a comet may increase due to the following factors: a) a nucleus layer is revealed whose evaporation yields a large amount of parent molecules of the condensed substances, or b) the intensity of hard electromagnetic or corpuscular radiation of the sun is increased, which leads to an increase in the chemical reactions whose products are condensed substances, or c) the conditions under which the nucleus of a solid phase is formed are improved -- for example, the degree of gas ionization is increased.

The reactions may be greatly intensified during excitation, dissociation, or ionization of the reacting molecules. These processes have a threshold, and require an activation energy. Therefore, hard radiation may have a decisive influence on the course of the reactions, although they make a small contribution to the total flux of solar radiation.

An increase in the amount of dust leads to intensification of the comet brightness. Thus, we may expect a correlation between the comet brightness and solar activity. It is known (Ref. 5) that this correlation has actually been observed. Sudden large flares, related to the formation of dust halos, may also be explained by the intensification of dust condensation due to the reasons given above. Just like each condensation, the halo formation does not require additional energy but, on the contrary, leads to its liberation. A change in the vapor chemical composition, and a change in the condensation rate associated with it, appear as a change in the comet brightness, even when the total amount of substance evaporated per unit time from a unit of the nucleus surface does not change.

The possible formation of dust particles as a result of gas condensation poses the problem of the comet nucleus structure in a new way. There is no necessity of assuming that it consists of ice which has been carefully mixed with dust particles having a specific size. We may assume that the nucleus substance has much greater physical uniformity, with a diverse chemical composition.

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